Effect of surface charge density on electret filters charge degradation by organic solvent exposure

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Abstract

The effect of the surface charge density of an electret filter on its collection efficiency degradation via isopropyl alcohol (IPA) species exposure is discussed in this study. Five electret filters with different electrostatic properties and identical physical properties were prepared and exposed to IPA species. Furthermore, the filtration performance was evaluated. Filters exposed to IPA droplets showed a drastic reduction in the collection efficiency. In addition, the electret filter with a higher surface charge density had a higher tolerance to IPA droplets, that is, the challenged IPA droplet amount that neutralized the electret filter with a high surface charge density ($= 5.0 \times 10^{-5} \text{ C/m}^2$) was 2.5 times higher than that of an electret filter with a low surface charge density ($= 1.9 \times 10^{-5} \text{ C/m}^2$). The results of this study revealed that there was a positive relationship between the surface charge density and challenged amount required to neutralize an electret filter.

Keywords: Challenged amount, Charge degradation, Electret filter, Isopropyl alcohol, Surface charge density

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1. Introduction

The COVID-19 pandemic has led to significant changes in the daily lifestyles of humans. People are required to wear a face mask when going out, and there are many restrictions on outdoor activities. According to previous studies, people spend more than 90% of their time indoors [1-3], however this time has increased since the outbreak of COVID-19 [4]. This situation has naturally led to improvements in air quality control to maintain human health. Fine particulate matter is introduced to the respiratory tract during breathing and causes various diseases such as asthma, pneumonia, cardiovascular disease, stroke, and cancer [5-10].

The air purifiers, equipped with electret filters, are generally used to remove particulate matter. Electret filters capture particulate matter effectively because of the strong electrostatic attraction between particles and the charged fiber at low pressure drop [11-18]. In particular, air purifiers are often used in hospitals to provide clean environments for patients. Hand sanitizers and skin disinfectants are frequently used to reduce infection with germs, which contain isopropyl alcohol (IPA), one of the most widely used organic solvents [19, 20]. However, IPA can negatively influence patients because it is highly volatile and can cause a variety of symptoms such as headache, dizziness, vomiting, nausea, and coma [21, 22]. Mar et al. [23] reported that the IPA concentration in the exhaled air of a hospital patient was approximately 2.5 times higher than that of the average person [23]. Furthermore, IPA negatively affects the filtration performance of an electret filter in an air purifier. Kim et al. reported a reduction in collection efficiency in an electrospun meta-aramid filter when exposed to IPA droplets [24]. It is well known that the decrease in collection efficiency is caused by electrostatic charge degradation [24-26].

Many researchers have attempted to elucidate the charge decay mechanism when an electret filtration system undergoes organic solvent exposure [27-29]. Rychkov et al. [27] reported that the charge decay of the electret filter could be attributed to internal charge collapse due to external ion deposition and masking. Biermann et al. [28] found that conductive solvents create conductive pathways around the fibers. Cantaluobe et al. [29] suggested that the charge decay was not the masking phenomenon on the fiber surface caused by the dipoles of the organic solvent, but that the charge collapse occurred because of the movement of the charge itself. Hence, despite various attempts, the charge decay mechanism of the electret filter remains uncertain. However, once charge degradation by IPA exposure occurs (due to the charge movements, or recombination, as suggested by Cantaluobe et al. [29]), an electret filter with a high surface charge density may take a longer time to be neutralized than that with a low surface charge density (Fig. 1).

To determine the relationship between the surface charge density and tolerance to an organic sorbent, electret filters with different surface charge densities were prepared, and the challenge amount was quantitatively investigated in this study.

2. Experimental Methods

2.1. Materials

The filtration performance of an electret filter is highly dependent on its physical structure and electrical properties. The filter thickness and fiber diameter were measured using a scanning electron microscope (SEM, JSM-5900, JEOL). The average fiber diameter was obtained by measuring more than 200 fibers using SEM imaging. The filter packing density, α was

determined by the relationship between the mass of a filter, W_f , the density of the fiber, ρ_f , and the volume of the filter, V , as shown in Eq. (1).

$$\alpha = \frac{W_f}{\rho_f V} \quad (1)$$

The physical properties of the test filters used in the experiment are listed in Table S1. The electrostatic effect should be determined while maintaining the physical properties of the filter constant. To determine the effect of surface charge density on the collection efficiency by organic solvent exposure, it is necessary to prepare test filters with different surface charge densities and with the same physical properties. However, it is quite difficult to prepare test filter media with different surface charge densities and the same physical properties. Therefore, a commercial polypropylene electret filter (E&H Co., Ltd., Republic of Korea), manufactured using the melt-blown method, was used as a Filter No. 1. Five electret filters with different surface charge densities were prepared by recharging Filter No. 1 under different charging conditions, such as applied voltage and treatment duration.

2.2. IPA Exposure of an Electret Filter

Fig. 2 shows the experimental setup used to measure both the droplet and vapor of the IPA species exposed to a test filter. Nitrogen gas was introduced into the impinger to generate IPA droplet and vapor at a flow rate of 1 L/min. The impinger was placed in a water bath (BW-20G, Lab Companion) at a temperature of 60 °C. The generated IPA droplets were measured using an aerodynamic particle sizer (model 3321, TSI) upstream of the filter. Both IPA droplets and vapors were trapped in Condenser 1 to determine the challenged IPA mass. The condenser was placed in a chiller (CBT-10, Lab Companion, Daejeon, Republic of Korea) set to a temperature

of -40°C. IPA droplet and vapor downstream of the filter were collected in condenser 2. The upstream and downstream sampling lines of the filter holder were kept as short as possible to minimize the deposition of IPA droplet and vapor in the tube line. Quantitative IPA amounts were measured using the Karl Fischer method (870 KF Titrino plus, Metrohm) [30], which calculates the amount of IPA by measuring the water concentration in the solution. The IPA purity was determined by measuring the water concentration upstream (condenser 1) and downstream (condenser 2) of the filter. The amount of IPA exposed to the filter was determined by subtracting the amount of downstream IPA from the amount of upstream IPA.

2.3. Filtration Performance of the Test Filters

Fig. 3 shows the experimental setup used to measure the filtration performance of the test filters. Compressed air was passed through a HEPA filter and flowed into an atomizer containing an aqueous NaCl solution (0.3–0.5 wt%). Polydisperse NaCl particles were generated by atomizing an NaCl solution in an atomizer at a flow rate of 3.2 L/min. The resulting droplets were introduced into a tubular furnace (Lindberg/Blue M, Thermo Fisher Scientific Inc.) controlled at 900°C, followed by a diffusion dryer to remove water species. The dried particles were conditioned to make the equilibrium charging state using a soft X-ray neutralizer (XRC-05, HCT CO., LTD, Icheon, Republic of Korea). Monodispersed singly charged particles were produced by passing them through a differential mobility analyzer (model 3081, TSI). The monodispersed uncharged particles were prepared using a soft X-ray neutralizer, then passed through a charged particle condenser. The size of the test particles ranged from 0.03 to 0.3 μm . The collection efficiency was determined by measuring the concentrations upstream and downstream of the

filter using a condensation particle counter (model 3775, TSI Inc.). The filtration velocity was controlled at a rate of 1–10 cm/s.

3. Results and Discussion

3.1. Estimation of Surface Charge Density

Many researchers have used the theoretical methodology to determine the surface charge density of a meltblown electret filter, where the net surface charge of the filter is almost zero [31, 32]. In filtration theory, uncharged ultrafine particles are captured in an uncharged filter by diffusion and interception capture mechanisms [33–36]. However, the additional dielectrophoretic capture mechanism is dominant when uncharged ultrafine particles pass through a charged filter [36, 37]. Assuming independent collection mechanisms, the following relationship among single fiber efficiencies can be observed. The single fiber efficiency between an uncharged filter and an uncharged particle, η_M is the sum of the single fiber efficiency by diffusion, η_D , and the single fiber efficiency by interception, η_R . In addition, the single fiber efficiency between a charged filter and an uncharged particle, η_{InM} is the sum of the single fiber efficiency by mechanical collection mechanisms, η_M , and the single fiber efficiency by dielectrophoretic force, η_{In} . Therefore, η_{In} can be obtained by subtracting η_M from η_{InM} , as shown in Eq. (3).

$$\eta_M = \eta_D + \eta_R \quad (1)$$

$$\eta_{InM} = \eta_D + \eta_R + \eta_{In} \quad (2)$$

$$\eta_{In} = \eta_{InM} - \eta_M \quad (3)$$

Otani et al. [38] suggested the prediction equations shown in Eqs. (4)~(6) for the dielectrophoretic force where η_{In} is expressed as a function of the dielectrophoretic force parameter K_{In} .

$$\eta_{In} = 1.48K_{In}^{0.93} \quad ; \quad 10^{-4} < K_{In} < 10^{-2} \quad (4)$$

$$\eta_{In} = 0.51h_k^{-0.35}K_{In}^{0.73} \quad ; \quad 10^{-2} < K_{In} < 1 \quad (5)$$

$$\eta_{In} = 0.54h_k^{-0.60}K_{In}^{0.40} \quad ; \quad 1 < K_{In} < 100 \quad (6)$$

$$K_{In} = \frac{(\varepsilon_p - 1)C_c \pi^2 Q_f^2 d_p^2}{6(\varepsilon_p + 2)\varepsilon_0(1 + \varepsilon_f)^2 \mu d_f u} \quad (7)$$

$$h_k = -0.5 \ln \alpha + \alpha - 0.25 \alpha^2 - 0.75 \quad (8)$$

where h_k is the hydrodynamic factor for the Kuwabara flow, ε_p is the permittivity of a particle (= 6.12 F/m), C_c is Cunningham's slip coefficient, Q_f is the surface charge density of an electret filter, d_p is the particle diameter, ε_0 is the permittivity of the vacuum ($= 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$), ε_f is the permittivity of a fiber ($= 2.2 \text{ C}^2/\text{N} \cdot \text{m}^2$), μ is the viscosity of air ($= 1.81 \times 10^{-5} \text{ N} \cdot \text{s}/\text{m}^2$), d_f is the fiber diameter, and u is the filtration velocity.

The following log-penetration equation describes the relationship between the collection efficiency of a filter and single fiber efficiency:

$$\eta = -\frac{\pi}{4} \frac{1-\alpha}{\alpha} \frac{d_f}{L} \ln(1-E) \quad (9)$$

where L is the filter thickness, and E is the collection efficiency of the filter.

The experimental single fiber efficiency, η_{In}^{exp} , can be obtained using Eq. (9). The η_{In}^{exp} values determined experimentally under specific filtration conditions were compared with the theoretical values by assuming the surface charge density of an electret filter. In other words, K_{In} is determined by the physical properties and Q_f of an electret filter. However, Q_f is an unknown

value because there is no direct measurement method available for melt-blown electret filters. The K_{In} values at specific filtration conditions under the arbitrarily assumed Q_f were determined and compared with the theoretical values calculated using Eqs. (4)~(6). Q_f can be determined where there is agreement between the experimental and theoretical single fiber efficiency values. Several other studies have used this methodology to determine the surface charge density of an electret filter [30, 38-40].

To determine the surface charge density using equations (1) to (6), the collection efficiencies of uncharged particles for both charged and uncharged filters are necessary. Because it is difficult to obtain an uncharged filter with the same internal structure as the charged filter, the uncharged filter was prepared by exposing the electret filter to IPA droplets according to the methodology outlined by Kim et al. [24], Xiao et al. [25], and Sachindou et al. [41]. Previous studies indicate that IPA plays a role in faster and more effective charge degradation than other organic solvents [25, 42]. Therefore, IPA (purity: 99.9%) was used to neutralize the test electret filters. It was further diluted using distilled water to precisely measure the amount of challenged IPA.

Fig. 4 shows the collection efficiencies of five electret filters and those of IPA-exposed filters for uncharged particles at a filtration velocity of 5.3 cm/s. As can be seen in Fig. 4(a), electret filters had a high collection efficiency of more than 80%, with whole particle sizes ranging from 0.03 to 0.3 μm . However, the IPA-exposed filters had a drastic reduction in collection efficiency for the test particles (Fig. 4(b)). The reduction in collection efficiency was due to the loss of electrostatic force between the electret filter and the uncharged particles, which can be explained by the shift of the most penetrating particle size (MPPS) to 200 nm [14, 24]. In

other words, diffusion and dielectrophoretic force were the dominant collection mechanisms for uncharged particles in electret filtration, which caused a decrease in MPPS [43, 44]. However, neutralization of the charged filter induced an increase in the MPPS.

The surface charge density of an electret filter can be calculated using the collection efficiencies shown in Fig. S2 and the physical properties of the filter. The prediction equations of the single fiber efficiencies due to pure dielectrophoretic force are expressed in Eqs. (4) to (6). As can be seen in the equations, single fiber efficiency is a function of the hydrodynamic factor and the dielectrophoretic force parameter. The hydrodynamic factor depends only on the packing density of the filter. However, the dielectrophoretic force parameter is a function of the surface charge density of the filter, particle diameter, fiber diameter, and filtration velocity.

Assuming the surface charge density of an electret filter, the dielectrophoretic force parameters can be determined for the given filtration conditions. Single fiber efficiencies due to the experimentally measured dielectrophoretic force, $\eta_{\text{In}}^{\text{exp}} = \eta_{\text{InM}}^{\text{exp}} - \eta_{\text{M}}^{\text{exp}}$, were plotted as a function of the dielectrophoretic force parameter and compared with those determined theoretically. The surface charge density assumed to provide the best fit with the theoretical line is the surface charge density of the filter.

Fig. 5 shows a comparison between the experimental and theoretical single fiber efficiencies. The surface charge densities, Q_f were 5×10^{-5} , 1.9×10^{-5} , 3.5×10^{-5} , 2.7×10^{-5} and $3.3 \times 10^{-5} \text{ C/m}^2$ for Filter No. 1 and Filter Numbers 2, 3, 4 and 5, respectively. The corona-treated filters had relatively lower surface charge densities than Filter No. 1, implying that corona recharging caused charge neutralization to take place. As can be seen in Fig. 4(a), Filter No. 1, followed by Filter No. 3, had the highest collection efficiencies, followed by Filter No. 5,

No. 4, and No. 2. The surface charge densities of the test filters were found to follow the same order, as shown in Fig. 5. The test filters had the same physical properties, resulting in the same mechanical collection efficiency. The difference in collection efficiency observed may be attributed to the differing dielectrophoretic forces of the test filters.

3.2. Size Distribution of Generated IPA Droplets

Quantitative phase analysis of the IPA species exposed to the test filter is important. Schuldt et al. [41] mentioned that the electrostatic charges in the electret filter were neutralized by saturated IPA vapors under the ISO 16890 standard [41]. However, both droplets and vapors are present when the vapor saturation ratio exceeds unity [45]. Our previous study showed that vapor-phase organic solvents do not influence the neutralization of an electret filter [30]. Therefore, the ratio of liquid phase IPA to IPA species should be quantified to determine the IPA challenge amount to neutralize an electret filter. Figure 6 shows the size distribution of the generated IPA droplets. As shown in the figure, the mean diameter in the droplet size distribution was $0.75\ \mu\text{m}$, and the geometric standard deviation was 1.24. The mass of the generated IPA droplets was determined by multiplying the obtained volume by the density of IPA. Based on the calculation results, it was confirmed that IPA droplets occupied 10.2% of the total IPA species.

3.3. Challenged IPA Droplet Amount Required to Neutralize the Electret Filter

As mentioned above, the test filters had different surface charge densities. In addition, we assumed that a filter with a high surface charge density might have a relatively lower decrease in the charge density due to IPA droplet exposure compared to a filter with a low surface charge

density. Therefore, the durability of filters with different surface charge densities to IPA droplets was investigated in this study.

Fig. 7 shows the changes in the collection efficiency of the test filters by the challenged IPA amount. As shown in Fig. 6, IPA droplets occupied approximately 10.2% of the total IPA (vapors and droplets). The upper X-axis in the graph shows the total quantity of IPA passing through the test filter, and the lower X-axis shows the quantity of IPA droplets substantially deposited in the test filter. Uncharged particles of 200 nm in size were used in the measurement, as they were found to have the largest difference in collection efficiency (Fig. 4(a)). Each test filter showed a drastic decrease in collection efficiency at a certain challenged IPA amount. The dramatic decrease in collection efficiency of Filter No. 1 appeared at the challenged IPA droplet amount of 8.67 g/m², compared with 3.47 g/m² for Filter No. 2, 7.96 g/m² for Filter No. 3, 6.63 g/m² for Filter No. 4, and 6.83 g/m² for Filter No. 5. The amount of IPA droplets challenged to neutralize Filter No. 1 ($Q_f = 5 \times 10^{-5} \text{ C/m}^2$) was approximately 2.5 times higher than that of Filter No. 2 ($Q_f = 1.9 \times 10^{-5} \text{ C/m}^2$). This result indicates that an electret filter with a higher surface charge density is durable in organic solvents. The collection efficiencies of the test filters exposed to an IPA droplet amount larger than the value were almost the same. To compare the lives of the filters exposed to IPA droplets, the collection efficiencies of IPA-exposed filters are plotted in Figure S3 as functions of the exposure time at the same IPA solution concentration. The filter with a high surface charge density maintained a high collection efficiency, although the filter was exposed to the IPA droplets for a longer time. It can be seen that the durability of filter No. 1 is 2.5 times that of filter No. 2., implying that a higher surface charge density induces a longer filter life.

The relationship between the surface charge density and challenged IPA droplet amount of the test filter is plotted in Figure 8. As shown in the figure, there is a linear relationship between the surface charge density and the challenged amount required to neutralize an electret filter. This relationship can be expressed as

$$S = 1.56 \times 10^5 Q_f + 1.601 \quad (10)$$

where Q_f is the surface charge density (C/m^2), and S is the challenged IPA droplet amount required to neutralize an electret filter (g/m^2).

4. Conclusions

Five electret filters with identical physical properties and different surface charge densities were evaluated to discover the relationship between the charge decay degree and surface charge density. The surface charge density of Filter No. 1 ($= 5.0 \times 10^{-5} C/m^2$) was approximately 2.5 times higher than that of Filter No. 2 ($= 1.9 \times 10^{-5} C/m^2$). In addition, the electret filter with the highest surface charge density (Filter No. 1) had a higher challenged IPA amount, that is, the amount required to neutralize the filter was higher than others. Based on the phase ratios of IPA droplets and vapors, the challenged IPA droplet amounts were $8.67 g/m^2$ for Filter No. 1 and $3.47 g/m^2$ for Filter No. 2. The former had about 2.5 times the challenged IPA droplet amount compared to the latter. A proportional relationship between the surface charge density and the challenged IPA droplet amount required to neutralize an electret filter was found. The electret filter with a higher surface charge density was found to have a higher resistance to IPA droplets, that is, one of the representative organic solvents. Based on these results, we can conclude that

the charging technology in electret filters should be improved to obtain the tolerance to organic species required in the current situation.

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Author Contributions

W.J.L. (Ph.D. student) conducted the research, investigation process, wrote and edited the manuscript. H.B.K. (Ph.D. student) conducted the research, visualized and data curation about the manuscript. H.J.U. (Ph.D) made funding acquisition and reviewed the manuscript. J.H.H. (Professor) supervised the student and advised about the manuscript. M-H.L. (Assistant Professor) supervised the student, concepted, wrote and edited the manuscript.

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